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Discrimination of Three-Phase Three-Limb Transformer Inrush Current Based on Characteristics of Instantaneous Excitation Inductances

Suonan Jiale, Liqiang Xu, Zaibin Jiao and Bin Du

Electrical Engineering Department Xi’an Jiaotong University Xi’an, China

Emai:sduxuliqiang@163.com

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Abstract. Existing methods utilizing excitation inductances to discriminate inrush current and internal fault of transformer are all derived from the singe-phase transformer circuit model, yet there are no discussions considering the widely used three-phase three-limb transformers. In view of this question, the mathematical model of three-phase three-limb transformer based on the characteristics of its magnetic equivalent circuit is established, through which the excitation inductances of the three-phase three-limb transformer can be calculated. The calculated excitation inductances have definite physical meanings and can reflect the saturation state of the transformer core under inrush condition. Analysis of the circuit model demonstrates that the delta circulating current is not the excitation current of three-phase three-limb transformer, so the proposed method can be used to the transformers with delta connection directly. The proposed method has been verified by electromagnetic transients program including direct current (EMTDC) simulations, simulation results show that the calculated excitation inductances have different characteristics under inrush and internal fault conditions, and can be applied to identify the inrush current of three-phase three-limb transformer.

Introduction

The major difficulty facing the power transformer protection is the discrimination between inrush current and internal fault. In recent years, new techniques based on the transformer instantaneous excitation inductance have been proposed to distinguish inrush current from internal fault. Using the winding voltage and the excitation current, the instantaneous excitation inductance of the transformer can be calculated. Under inrush condition, the transformer core works under saturated condition and unsaturated condition alternately. When under unsaturated condition, the magnetic permeability of transformer core is very high, and the instantaneous excitation inductance is relatively large; while under saturated condition, the magnetic permeability of transformer core is very small, so is the excitation inductance. The instantaneous excitation inductance varies between large value and relatively very small value alternately and can reflect the saturation condition of transformer core under inrush condition. When internal fault occurs to the transformer, the calculated inductance parameter is very small and basically doesn’t change. Based on these characteristics, inrush current can be identified [1-4].

The schemes utilizing transformer excitation inductance described in [1-4] are all based on the T-type equivalent circuit model of the single-phase transformer, so are the simulation and experimentation. While， for the widely used three-phase three-limb transformers in power system, there aren’t any discussions dedicated to it yet.

In common calculative use in power systems, such as short circuit current calculation, power flow calculation, the focus is in fact on the relationship between coil voltage and coil current under unsaturated condition, the excitation current of the transformer can be neglected in this case, so same model is used to three-phase bank composed of single-phase transformers and three-phase three-limb transformer except the difference of zero sequence parameters. But the excitation inductance which varies according to the saturation state of the transformer core represents the relationship between winding voltage and excitation current, in this condition there are differences between three-phase bank and three-phase three-limb transformer.

First, for three-phase three-limb transformer, there are mutual magnetic fluxes between phases through transformer core. So in terms of each winding voltage, all three phase currents are its excitation currents corresponding to the main magnetic flux. Because of the structure of the core, the inductance parameters of three-phase three-limb transformer are asymmetric, and the degree of the asymmetric is affected by the asymmetric saturation state of the transformer core. This makes the three-phase three-limb transformer unable to be break down into three independent T-type circuit models. For three-phase three-limb transformer, the inductance parameters calculated through T-type model have no definite physical meanings, and can't correctly reflect the saturation condition of the core. So their characteristics are difficult to analyze, and also difficult to be used in deciding the transformer protection criterion.

In addition, for the transformer with wye-delta connection, the role played by delta side circulating current (which is also the zero-mode component of winding current) in three-phase bank and three-phase three-limb transformer is different. For the three-phase bank, delta side circulating current is part of the excitation current. When calculating excitation inductance, because the delta side winding currents can't be measured in most cases, considerate error may be yielded if neglecting the delta side circulating current, and make it difficult to distinguish inrush current from internal fault. Reference [4-5] discussed measures aimed to solve this problem. While for three-phase three-limb transformer, zero-mode component of the winding current can't induce main magnetic flux which completely circulating in the core and the magnetic flux it produced have to pass through transformer oil and oil tank. The corresponding inductance is much less than the excitation inductance, so the delta side circulating current is no part of the excitation current of the three-phase three-limb transformer.

In this paper, based on the characteristics of the three-phase three-limb equivalent magnetic circuit, the mathematical model to calculate the excitation inductances of three-phase three-limb transformer is established. The excitation inductances calculated have definite physical meanings and can reflect the saturation condition of transformer core under inrush condition. Thus the excitation inductances calculated can be used to identify the inrush current of three-phase three-limb transformer. The method proposed in this paper is verified by simulation.

Mathematical Model of Three-Phase Three-Limb Transformer

For the two winding three-phase three-limb transformer showed in Fig.1, it's magnetic fluxes distribution is showed in Fig.2 [6-10].

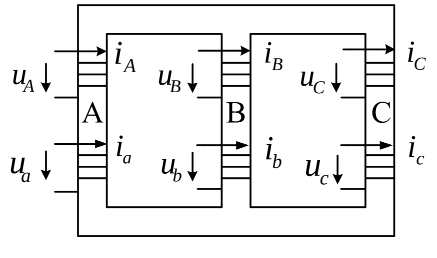

Figure 1. Three-phase three-limb transformer

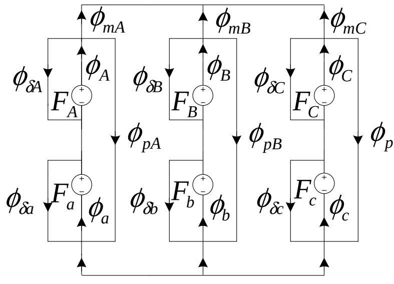

Figure 2. Magnetic fluxes distribution of three-phase three-limb transformer

u_A, i_A, u_a, i_a are primary and secondary winding voltages and winding currents of limb A. u_B, i_B, u_b, i_b are primary and secondary winding voltages and winding currents of limb B. u_C, i_C, u_c, i_c are primary and secondary winding voltages and winding currents of limb C. Assume primary and secondary windings have the same turns of wire number n.

ϕ_A, ϕ_B, ϕ_C, ϕ_a, ϕ_b and ϕ_c are total fluxes passing through each winding respectively. $\phi_{\delta A}$, $\phi_{\delta B}$, $\phi_{\delta C}$, $\phi_{\delta a}$, $\phi_{\delta b}$, and $\phi_{\delta c}$ are leakage fluxes which only passing through one winding; ϕ_{pA}, ϕ_{pB} and ϕ_{pC} are leakage fluxes passing through the two windings of the same limb; ϕ_{mA}, ϕ_{mB} and ϕ_{mC} are the main fluxes of every winding, which completely passing through transformer core. Taking winding A as an example, ϕ_A can be expressed as:

$$\phi_A = \phi_{\delta A} + \phi_{pA} + \phi_{mA} \tag{1}$$

ϕ_{mA} can be divided into three parts: magnetic flux ϕ_{mAA} is produced by the windings of limb A, magnetic flux ϕ_{mBA} is induced by windings of limb B, and magnetic flux ϕ_{mCA} induced by windings of limb C. So (1) can be expressed as:

$$\phi_A = \phi_{\delta A} + \phi_{pA} + \phi_{mAA} + \phi_{mBA} + \phi_{mCA} \tag{2}$$

The magnetic circuit of ϕ_{pA}, ϕ_{pB}, ϕ_{pC} is the zero-sequence magnetic circuit of the three-phase three-limb transformer, which composes of transformer core, transformer oil and oil tank. Taking limb A for example, ϕ_{pA} only passes through the two windings of limb A, its excitation current is $i_A + i_a$, and the corresponding inductance is the zero-sequence excitation inductance of the three-phase three-limb transformer L_0. So ϕ_{pA} can be expressed as:

$$\phi_{pA} = L_0(i_A + i_a)$$

Neglect the equivalent resistors of copper losses and no load losses. Based on electromagnetism induction law and (2):

$$u_A = L_\delta \frac{di_A}{dt} + L_0 \frac{di_{da}}{dt} + L_{AA} \frac{d(i_{da})}{dt} + L_{AB} \frac{d(i_{db})}{dt} + L_{AC} \frac{d(i_{dc})}{dt} \tag{3}$$

i_{da}, i_{db} and i_{dc} in (3) are the differential winding currents of each limb. Where $i_{da} = i_A + i_a$, $i_{db} = i_B + i_b$, $i_{dc} = i_C + i_c$. L_δ is the leakage inductance of primary winding.

L_{AA}, L_{AB} and L_{AC} are excitation instantaneous inductances corresponding to main flux of three-phase three-limb transformer, L_{AA} is self excitation inductance of windings around limb A, L_{AB} and L_{AC} are mutual excitation inductances between windings of different limbs.

ϕ_{mAA} is the main flux produced by windings of limb A and loops through limb B and limb C, so ϕ_{mAA} is divided into two parts: ϕ_{AB} is the part passing through limb B, ϕ_{AC} is the part passing through limb C. L_{AA}, L_{AB} and L_{AC} can be defined by (4).

$$\begin{cases} L_{AA} = n\dfrac{d\phi_{mAA}}{di_{da}} \\ L_{AB} = n\dfrac{d\phi_{AB}}{di_{da}} \\ L_{AC} = n\dfrac{d\phi_{AC}}{di_{da}} \end{cases} \tag{4}$$

Obviously ϕ_{mAA}, ϕ_{AB}, ϕ_{AC} have the relationship:

$$\phi_{mAA} = -(\phi_{AB} + \phi_{AC}) \tag{5}$$

So excitation inductances have the following relationship:

$$L_{AA} = -(L_{AB} + L_{AC}) \tag{6}$$

Appling excitation inductance relationship (6) to (3) yields:

$$u_A = L_\delta \frac{di_A}{dt} + L_0 \frac{di_{da}}{dt} + L_{AB} \frac{d(i_{db} - i_{da})}{dt} + L_{AC} \frac{d(i_{dc} - i_{da})}{dt} \tag{7}$$

The above derivation can also be applied to windings of limb A and limb B.

$$L_{BB} = -(L_{AB} + L_{BC}) \tag{8}$$

$$L_{CC} = -(L_{AC} + L_{BC}) \tag{9}$$

Denote $i_{dab} = i_{da} - i_{db}$, $i_{dbc} = i_{db} - i_{dc}$, $i_{dca} = i_{dc} - i_{da}$, applying the relationship of (8) and (9) to limb B and limb C windings.

$$\begin{cases} u_A = L_{1\delta}\dfrac{di_A}{dt} + L_0\dfrac{di_{da}}{dt} + L_{AA}\dfrac{di_{dab}}{dt} + L_{AC}\dfrac{di_{dcb}}{dt} \\ u_B = L_{1\delta}\dfrac{di_B}{dt} + L_0\dfrac{di_{db}}{dt} + L_{BB}\dfrac{di_{dbc}}{dt} + L_{AB}\dfrac{di_{dac}}{dt} \\ u_C = L_{1\delta}\dfrac{di_C}{dt} + L_0\dfrac{di_{dc}}{dt} + L_{CC}\dfrac{di_{dca}}{dt} + L_{BC}\dfrac{di_{dba}}{dt} \end{cases} \tag{10}$$

Equation (10) reflects the relationship between winding voltage and the winding currents of the three-phase three-limb transformer.

Mathematical Model to Calculate Excitation Inductances of Three-Phase Three-Limb Transformer

Equation (10) shows that each winding voltage of the three-phase three-limb transformer can be divided into leakage magnetic fluxes induced voltage and main magnetic flux induced voltage. The excitation current corresponding to the main flux is the subtraction between differential currents from two different limbs.

With rated voltage and current as reference value, the leakage inductance is less than 30% generally, zero-sequence excitation inductance is about 30%~ 100%generally. While the excitation inductance corresponding to the core magnetic circuit can reach up to 10000% when working under unsaturated condition; even under saturated condition, it is much larger than the leakage inductance. Obviously it is the excitation currents corresponding to main fluxes which can reflect the saturation state of the transformer core under inrush condition.

So (11) is applied as the mathematical model to calculate excitation inductances of the three-phase three-limb transformer.

$$\begin{cases} u_A = L_{AA}\dfrac{di_{dab}}{dt} + L_{AC}\dfrac{di_{dcb}}{dt} \\ u_B = L_{BB}\dfrac{di_{dbc}}{dt} + L_{AB}\dfrac{di_{dac}}{dt} \\ u_C = L_{CC}\dfrac{di_{dca}}{dt} + L_{BC}\dfrac{di_{dba}}{dt} \end{cases} \tag{11}$$

The excitation current corresponding to main magnetic flux of three-phase three-limb transformer is the subtraction between currents (differential current of each limb) of two different limbs, so the zero-mode current components are eliminated. This also shows that the zero-mode current component is not part of excitation current of three-phase three-limb transformer, its corresponding excitation inductances are leakage inductance and zero-sequence inductance. This character of three-phase three-limb transformer is different from three-phase bank.

For three-phase bank, the excitation current corresponding to its main flux is the differential current of each phase, which contains the zero-mode current component, so the delta side circulating current is part of the excitation current. When energized, the excitation inductance corresponding to delta side circulating current is very large especially while the transformer core works under unsaturated condition. When calculating excitation inductance, considerate error may be yielded when neglecting the delta side circulating current, and make it difficult to distinguish inrush current from internal fault.

For three-phase three-limb transformer with wye-delta connection, the delta side circulating current is no part of its excitation current, and have limited effect when calculating excitation inductances. In fact, line currents of delta side are the subtractions between winding currents. Fig.3 shows the connection of a three-phase three-limb transformer with wye-delta connection, where i_{la}, i_{lb}, i_{lc} are the line currents that can be measured on delta side. The relationship between winding currents and line currents of delta side is given by (12).

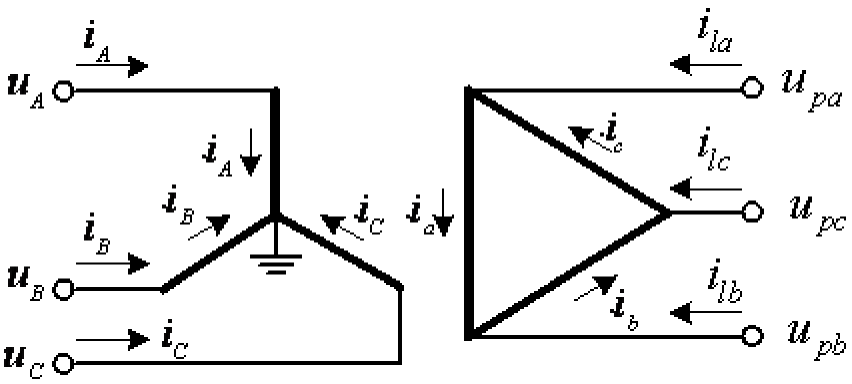

Figure 3. Current of the transformer with wye-delta connection

$$\begin{cases} i_{la} = i_a - i_c \\ i_{lb} = i_b - i_a \\ i_{lc} = i_c - i_b \end{cases} \tag{12}$$

So the excitation currents of the transformer showed in Fig. 3 are:

$$\begin{cases} i_{da} - i_{db} = i_A - i_B - i_{lb} \\ i_{db} - i_{dc} = i_B - i_C - i_{lc} \\ i_{dc} - i_{da} = i_C - i_A - i_{la} \end{cases} \tag{13}$$

With the excitation currents expressed in (13), the excitation inductances of the transformer showed in Fig.3 can be calculated based on (11).

Using (11) to calculate the excitation inductances of transformer is in fact neglecting the effect of the leakage magnetic fluxes. Take winding A for example. When the transformer core circular path corresponding to the winding A main flux works under unsaturated condition, the most flux passing through winding A is main flux. So ignoring leakage fluxes only yields little error and the calculated inductance has large value under this condition. When the corresponding core loop works in saturated state, the proportion of the leakage fluxes in the total flux is comparatively larger than unsaturated condition, so is the calculative error of the excitation inductances. However, the excitation inductance parameters itself is very small under this condition, hundreds of times smaller than unsaturated condition, so the values of the calculated excitation inductances are very small even with relatively larger error.

Simulation

The transformer model used is the UMEC three-phase three-limb transformer model of simulation software PSCAD/EMTDC. The rating capacity is 240MVA, transform ratio 220kV/110kV，no load losses is 130kW, copper losses 600kW, zero-sequence excitation inductance is 0.6 per-unit value, the length ratio of yoke/limb is 1.58. The transformer core gets saturated at 1.1pu voltage. Sampling frequency is 2000Hz. Least square method is adopted to calculate inductance parameters.

In order to verify the analysis of the delta side circulating current when calculating the excitation inductances of the three-phase three-limb transformer. For the same transformer model and same switching angle of winding voltage, the excitation inductances are calculated under three energizing conditions respectively.

Case 1:Wye-wye connected.

Case 2:Wye-delta connected, energized on wye connection side.

Case 3:Delta-wye connected, energized on delta connection side.

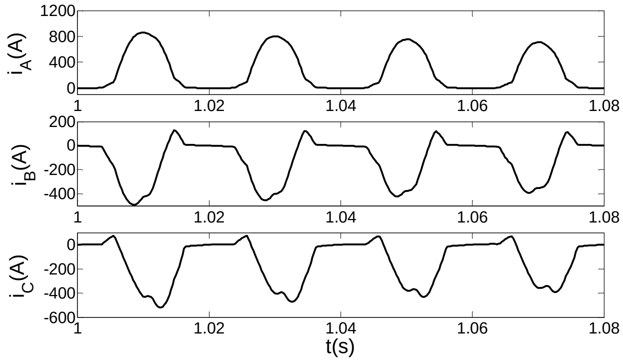

Figure 4. Inrush currents on wye connection side in switching Case 1

The winding connection of Case 2 and Case 3 is set as the same as showed in Fig.3. So the excitation currents are obtained according (12). All three switching cases above in fact are the same to the transformer iron core although different in zero-mode current. So the calculated excitation inductances should be the same under all three switching conditions.

Fig.4 shows the inrush current in switching Case 1, Fig.5 shows the calculated excitation self-inductances of windings from each limb based on equation (11).

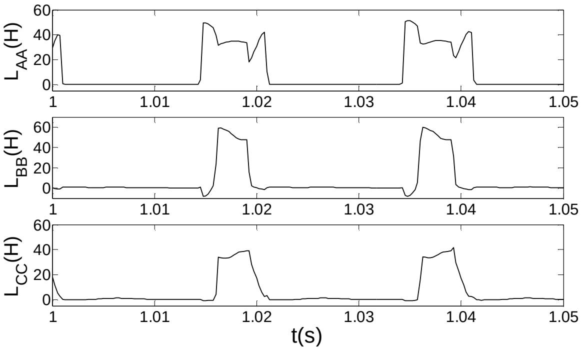

Figure 5. Instantaneous self inductances of the transformer in switching Case 1

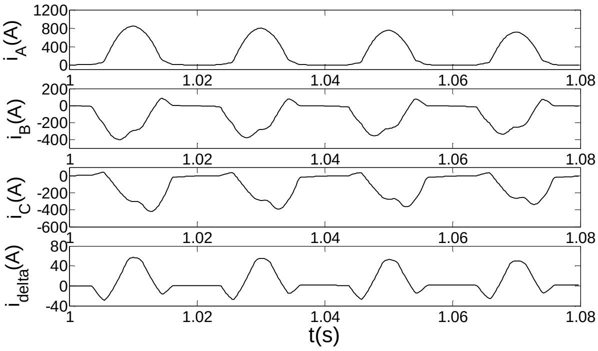

Figure 6. Inrush currents on wye side and circulating current on delta side in switching Case 2

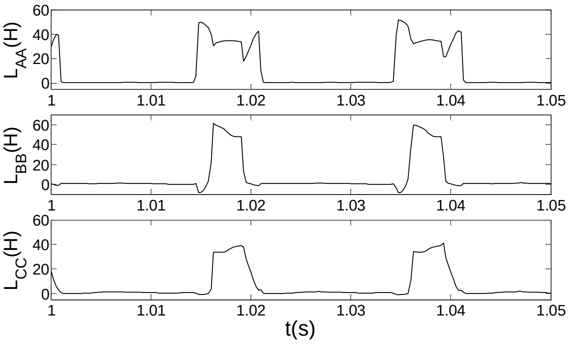

Figure 7. Instantaneous self inductances of the transformer in switching Case 2

Fig.6 shows the inrush currents and delta side circulating current in switching Case 2. i_{delta} represents delta side circulating current. Fig.7 shows the calculated excitation inductances in this case.

Fig.8 shows the inrush currents and delta side circulating current in switching Case 3. Where i_{lineA} , i_{lineB} and i_{lineB} denote line currents on delta side (primary side). Fig.9 shows the calculated self-inductances of windings from each limb in this case.

The simulation results above shows that when energized, the transformer core woks under unsaturated condition and saturated condition alternatively, causing the instantaneous excitation inductances vary drastically. The time cycle of variations is the same to winding voltage cycle.

Although the zero-mode currents are different from each other in the three switching cases, the instantaneous excitation inductances calculated i are basically the same, indicating that the delta side circulating current is no pat of the excitation current of three-phase three-limb transformer, and has little effect when calculating excitation inductances.

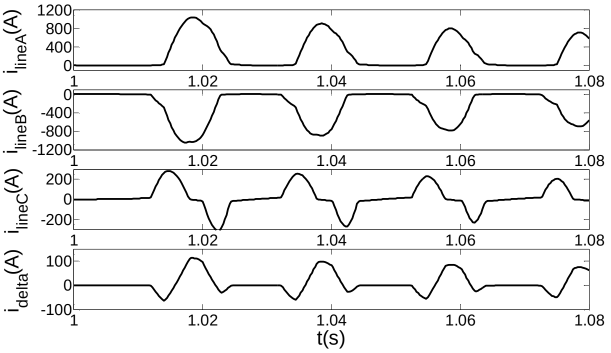

Figure 8. Inrush current and circulating current on delta side in switching Case 3

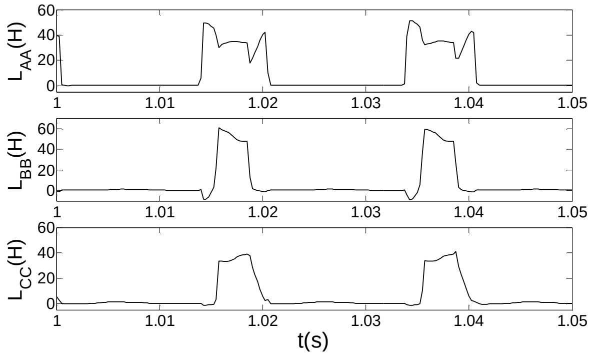

Figure 9. Instantaneous self inductances of the transformer in switching Case 3

When internal fault occurs to the transformer, the winding currents and voltages don’t have the relationship expressed in (10), and the excitation inductances calculated in this condition have no physical meanings as under inrush condition. Generally 1% turn-to-turn fault can yield 1 pu differential current. In this paper, internal fault of different degrees have been simulated and the excitation inductances have been calculated respectively. Fig.10 shows the typical characteristics of the calculated excitation inductances when internal fault occurs to the winding of limb A no matter which connection type is adopted. The simulation indicates that when internal fault occurs, the related excitation inductance have a very small value which basically doesn’t change.

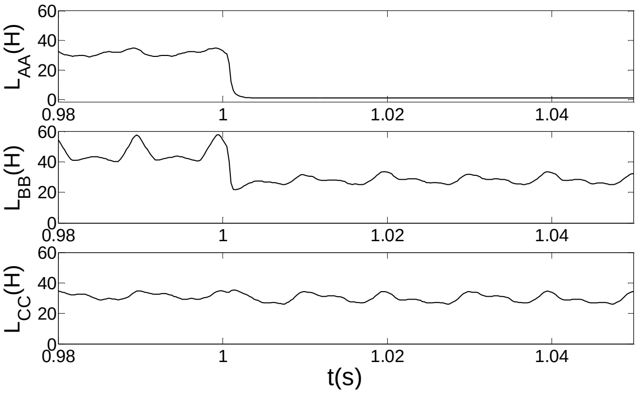

Figure 10. Instantaneous self inductances of the transformer with limb A winding internal fault

The simulation results prove that when energized, the excitation inductances of three-phase three-limb transformer can be calculated using the method proposed in this paper no matter which connection type is adopted. The calculated inductances vary drastically with the saturation state of transformer core. When internal fault occurs to the transformer, the related parameter calculated has very small value and little variation. The distinction between inrush and internal fault conditions is very clear and can be applied to the three-phase three-limb transformer protection.

Conclusions

In this paper, based on the magnetic characteristics of three-phase three-limb transformer, the relationship between excitation inductance corresponding to main fluxes is analyzed, and the mathematical model to calculate excitation inductances is established. The calculated inductance presents distinct different characteristics under inrush and internal fault conditions and can be applied to construct three-phase three-limb transformer inrush current identification scheme. The proposed method can be applied to three-phase three-limb transformer with wye-delta connection directly. The work presented in this paper has certain theoretical and practical value on the application of excitation inductance based protection principle to the three-phase three-limb transformer.

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